Desalination processes revisited

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Overview

1. Why care about salinity?
2. The salinity evolution of sea ice
   - Initial salt release
   - Diffusion
   - Brine expulsion
   - Gravity drainage
   - Flushing
3. Outlook

Overview

1 Why care about salinity?

2 The salinity evolution of sea ice
- Initial salt release
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3 Outlook

Importance of sea-ice salinity

Physical properties of sea ice

- The salinity and the temperature of sea ice determine its solid fraction *(Danny's talk)*
- The heat capacity, heat conductivity, optical properties and mechanical properties are hence directly influenced by the salinity profile

Interaction with the ocean

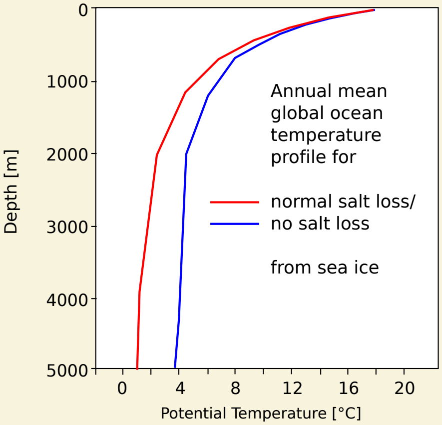
- Salt release from sea ice alters the salinity distribution of the underlying ocean and can drive deep convection

Sensitivity of sea ice to global warming

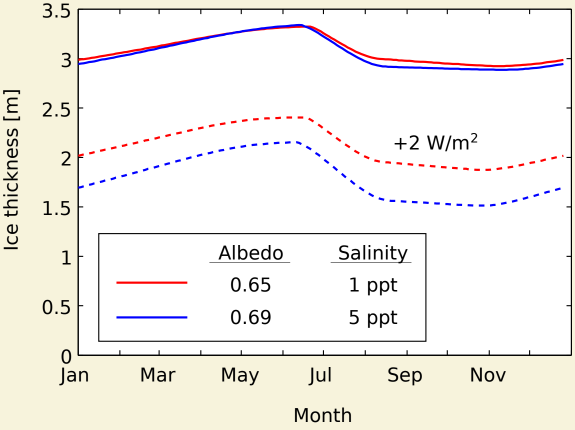
- The sensitivity of sea ice to global warming depends crucially on its salinity

Ocean convection

Salt loss from sea ice is important for deep convection in Southern Ocean



Sensitivity to warming



Overview

Processes that might contribute

Traditional view

- Initial salt release (most important)
- Diffusion (negligible)
- Brine expulsion (important for thin ice)
- Gravity drainage (important)
- Flushing (important)

Overview

Importance

Traditional view

- *Weeks and Lofgreen*, 1967: All salt release from sea ice can be explained by a fractionation coefficent for salt release at the advancing front. (Theoretical background: model by *Burton, Prim and Slichter* (1956) for single-crystal alloys)

Importance

Traditional view

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- *Maykut and Untersteiner*, 1971: 90% of salt is released at the advancing front

Importance

Traditional view

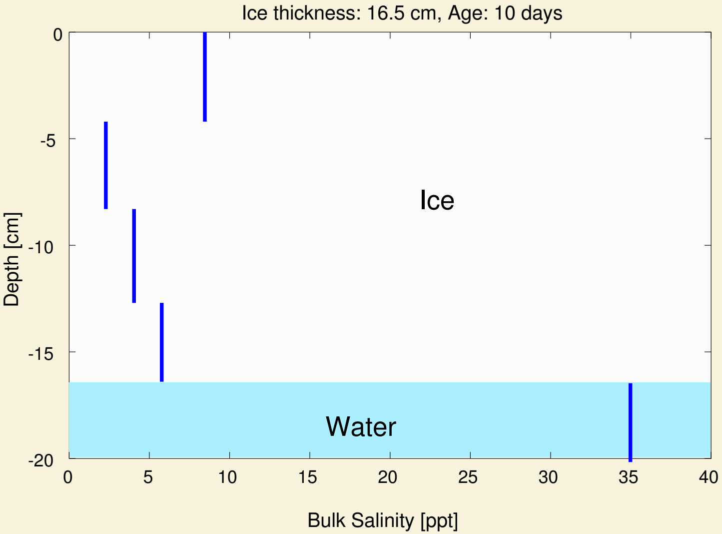
- *Weeks and Lofgreen*, 1967: All salt release from sea ice can be explained by a fractionation coefficent for salt release at the advancing front. (Theoretical background: model by *Burton, Prim and Slichter* (1956) for single-crystal alloys)
- *Maykut and Untersteiner*, 1971: 90% of salt is released at the advancing front
- *Cox and Weeks*, 1988: Salinity at the front is determined by ice-growth velocity, between 30% and 90% of salt is released directly at the advancing front

The ice–ocean interface

Solution of mushy-layer equations gives:

- continuous temperature field across the ice–ocean interface
- continuous solid-fraction field across the ice–ocean interface (for realistic diffusivities)
- hence a continuous bulk-salinity field across the ice–ocean interface

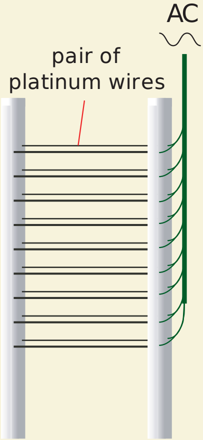
But measurements from ice cores show:

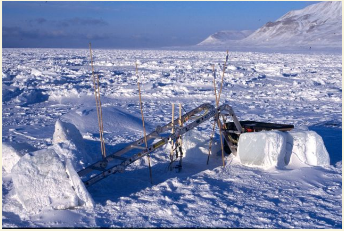


“It doesn’t matter how beautiful your theory is,
It doesn’t matter how smart you are;
if it doesn’t agree with experiment, it’s wrong.”

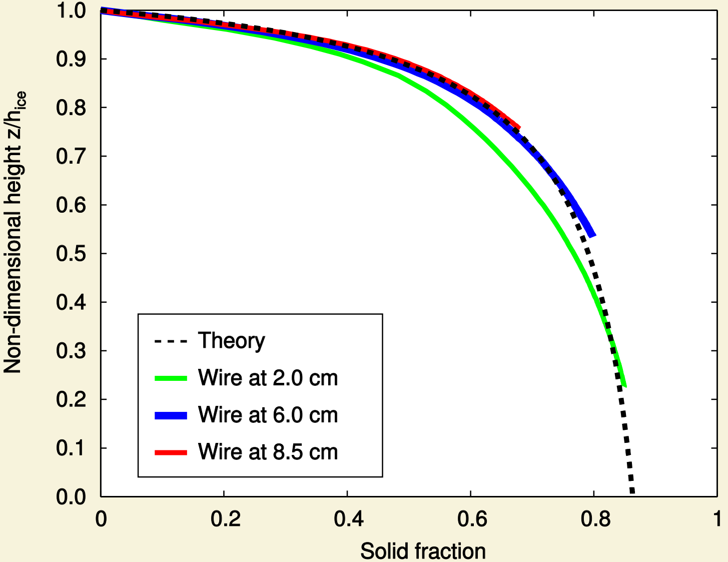
Richard Feynman

The wire harp

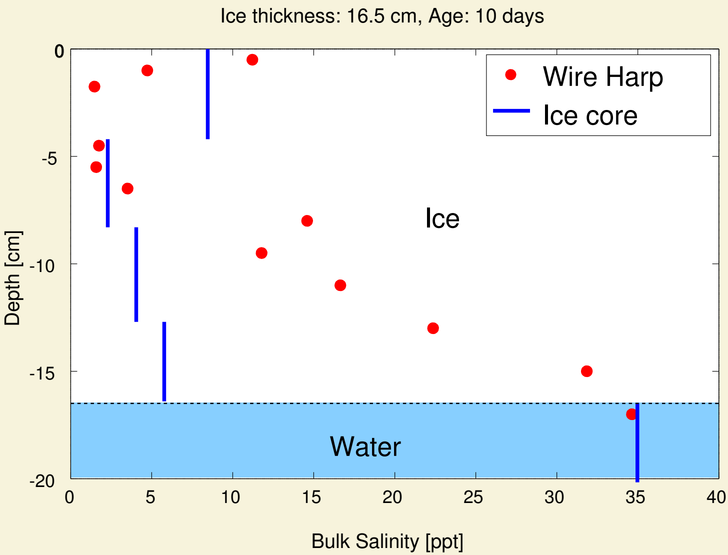




Comparison with theory



Field Measurements



Conclusion for modelling

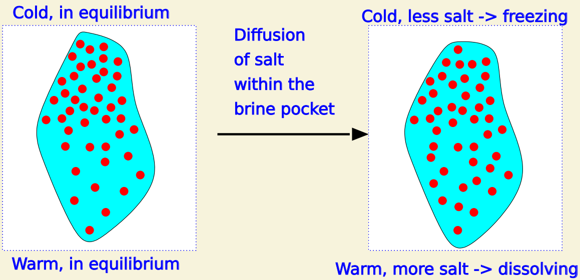
Initial salt expulsion

No salt is lost from sea ice at the advancing front.

We do hence not need to model this process.

Overview

Diffusion I



Consequence: “anomalous” diffusion against the temperature gradient

Proposed by *Whitman* (1926) to be responsbile for most salt loss from sea ice. Shown to be insignificant by various authors in the 1960s (e.g., *Untersteiner* (1968))

Diffusion II

What about diffusion in the inter-connected brine network?

Conservation of salt:

$$\frac{\partial \rho_m S_{bu}}{\partial t} = \rho_l \nabla \cdot ((1-\phi) D \nabla S_{br}) - \nabla \cdot (\rho_l S_{br} \mathbf{U})$$

Using $(1-\phi_m) = S_{bu}/S_{br}$ this can be re-written as

$$\frac{\partial \rho_m S_{bu}}{\partial t} = -\nabla \cdot (\rho_m S_{bu} \mathbf{v}) - \nabla \cdot (\rho_l S_{br} \mathbf{U}).$$

Here,

$$\mathbf{v} = \frac{D}{S_{br}} \nabla S_{br} \approx O(1) cm/year$$

is the apparent advection velocity caused by diffusion.

Conclusion for modelling

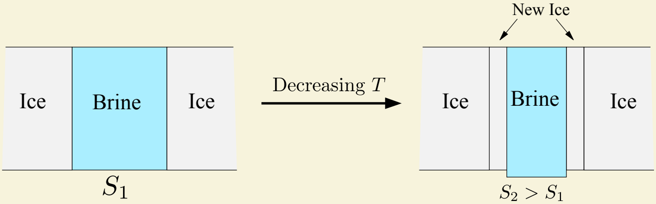
Diffusion

Diffusion of salt is extremely slow ($O(1)$ cm/year).
We do hence not need to model this process.

Overview

Brine expulsion I

What happens, when sea ice gets colder?



- The salinity of the brine must increase, hence some of the water in the brine freezes to form new, pure ice
- The forming ice has a lower density than the brine and occupies a larger volume
- The brine is “squeezed” downwards (or upwards)

Cox and Weeks, 1975: Crucial for salt loss from thin ice

Brine expulsion II

The brine-velocity field caused by internal phase changes

$$\frac{\partial \overline{U}}{\partial z} = \left(1 - \frac{\rho_s}{\rho_l}\right) \frac{\partial \phi}{\partial t}$$

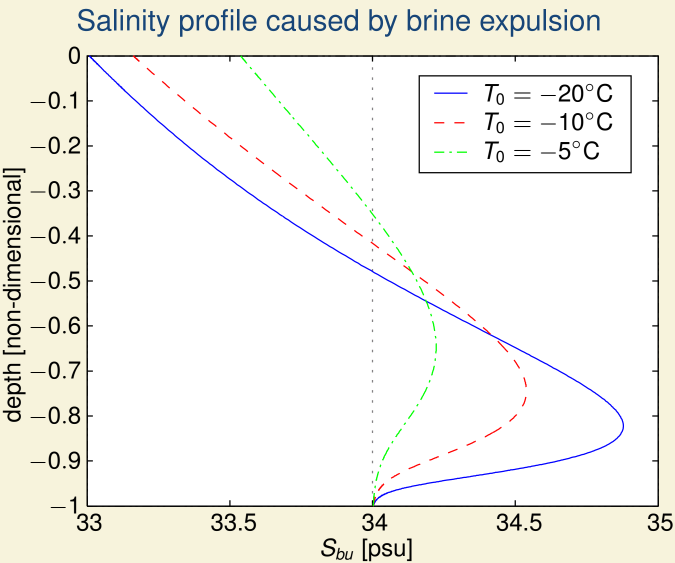
can be integrated over the entire ice thickness h

$$\int_0^{h(t)} \frac{\partial \overline{U}}{\partial z} \mathrm{d}z = \left(1 - \frac{\rho_s}{\rho_l}\right) \int_0^{h(t)} \frac{\partial \phi}{\partial t} \mathrm{d}z$$

to give

$$\begin{aligned}
\overline{U}(h) &= \left(1 - \frac{\rho_s}{\rho_l}\right) \left(-\frac{\mathrm{d}h}{\mathrm{d}t}\phi(h) + \frac{\mathrm{d}}{\mathrm{d}t} \int_0^{h(t)} \phi \mathrm{d}z\right) \\
&< \left(1 - \frac{\rho_s}{\rho_l}\right) \dot{h} \\
&< \dot{h}
\end{aligned}$$

Brine expulsion III



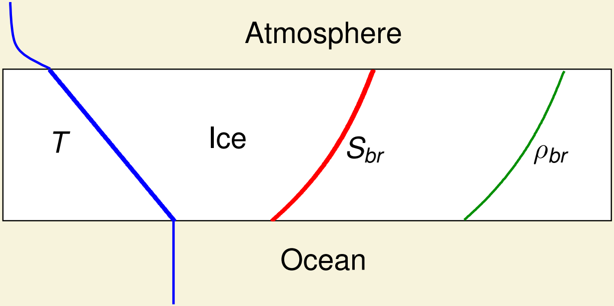
Conclusion for modelling

Brine expulsion

Brine expulsion only leads to some (small) *internal* re-distribution of salt.
Hence, it does not need to be modeled within any large-scale sea-ice model.

Overview

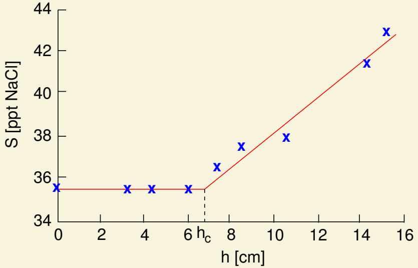
Gravity drainage I



Instable brine-density profile *can* cause convection.

Gravity drainage II

Water salinity underneath growing sea ice (in lab experiment)

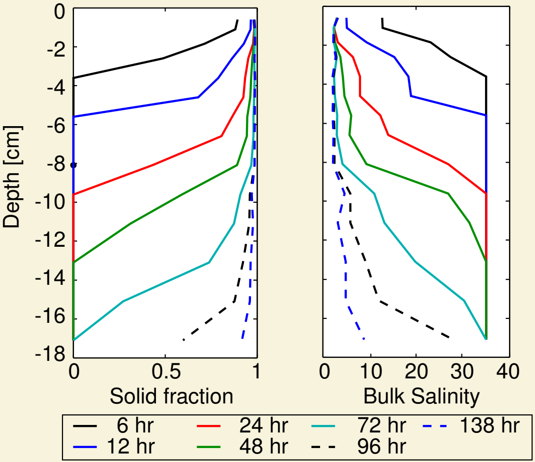


Convection is governed by a Rayleigh-number (Danny's talk)

$$Ra = \frac{\overbrace{\rho_l \beta \Delta S}^{\Delta\rho} \, gh \Pi(\bar{\phi})}{\kappa \mu}$$

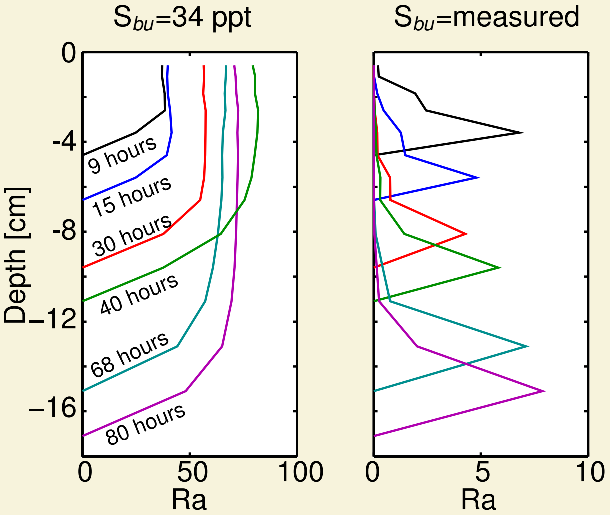
Gravity drainage III

Results from field measurement



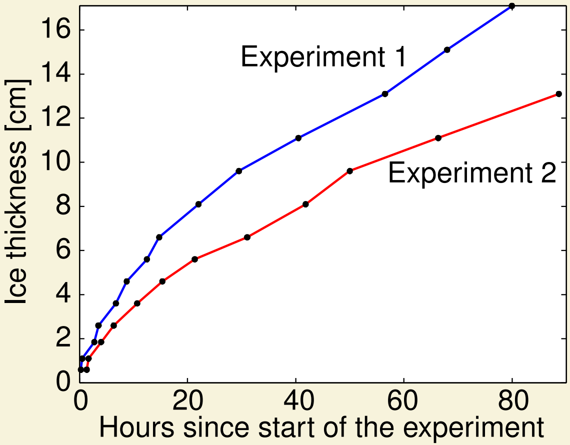
Gravity drainage IV

Results from field measurement (note different scales!)



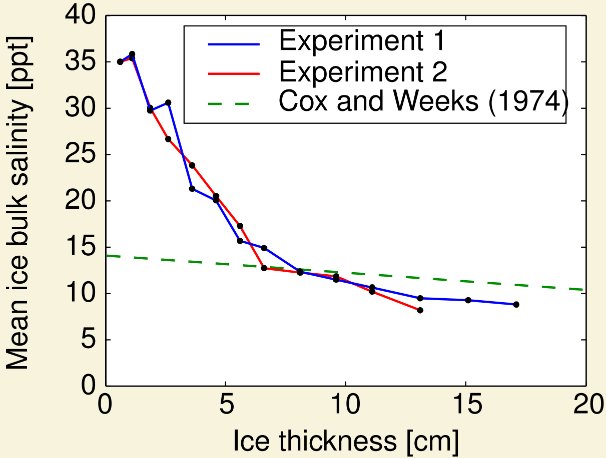
Gravity drainage V

Comparison Field experiment I and II, Svalbard, March 2005



Gravity drainage VI

Despite different growth rates, very similar salinity evolution



Conclusion for modelling

Gravity Drainage

Gravity drainage is *the only* process that must be included into a climate model to account for salt loss during winter.

Using a dynamical approach based on a critical Rayleigh number reflects the underlying physics and allows for an efficient numerical scheme.

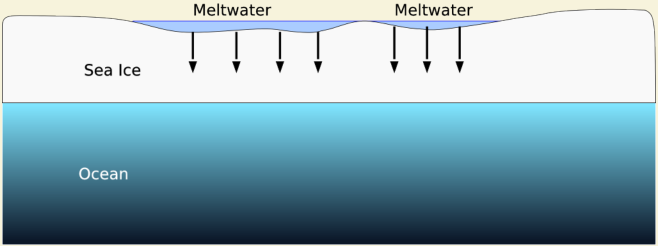
A simple empirical approach might be better than not doing anything.

Overview

Melt ponds

Photo: Peter Guest

Brine movement by flushing



Can be described as flow through a porous medium governed by Darcy's law

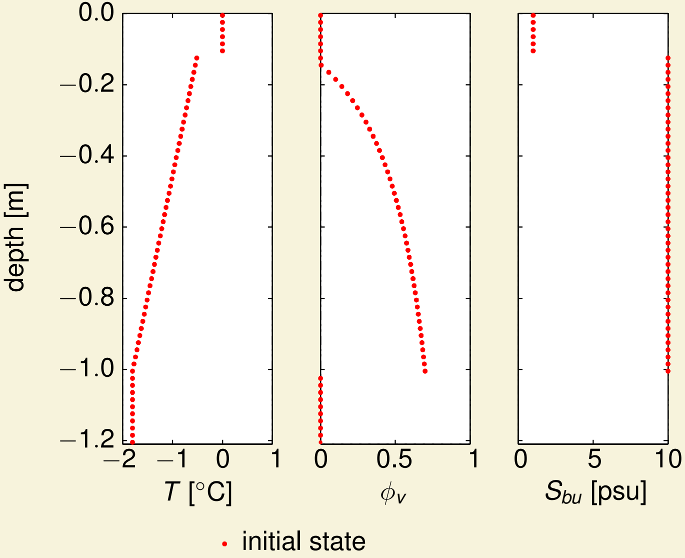
$$\frac{\Delta z}{\Delta t} = -\rho g \frac{\Pi_{min} z_{mp}}{\mu h}$$

Empirically:

$$\Pi = 2 \cdot 10^{-8}(1-\phi)^{3.1}\,\mathrm{m}^2$$

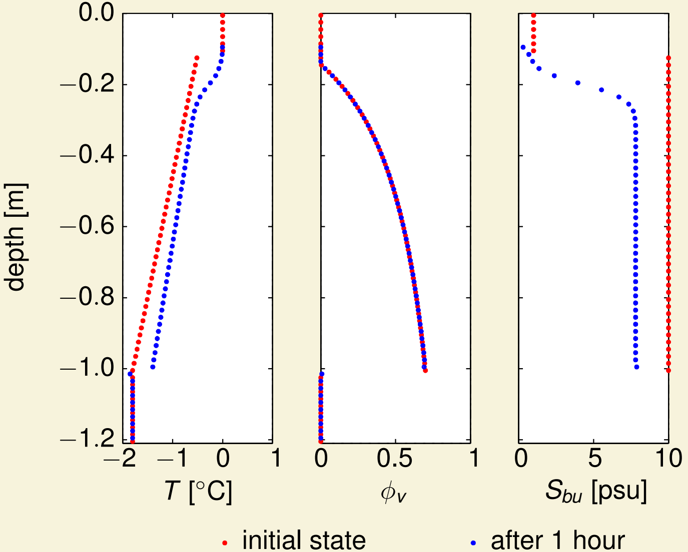
e.g., *Eicken*, JGR, 2002

Flushing



depth [m]
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−2 −1 0 1
T [°C]
0 0.5 1
ϕ_v
0 5 10
S_{bu} [psu]
initial state

Flushing


0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
depth [m]
−2 −1 0 1
T [°C]
0 0.5 1
ϕ_v
0 5 10
S_{bu} [psu]
initial state
after 1 hour

Conclusion for modelling

Flushing

Flushing leads to a further decrease of salinity during summer.

For a known bulk salinity, the permeability of the ice can be estimated and flushing can be modeled using Darcy's law.

Overview

How does frazil ice evolve?

Activities

- Lab experiments on sea-ice evolution in a small wave tank (evolution of ice volume, salt fluxes, heat fluxes, from October 2010)
- Development of instrument to measure frazil concentration in situ (ongoing)
- Field experiment on sea-ice evolution in a wave field (probably from October 2011)

Measuring the salinity evolution of sea ice

Activities

- Lab experiments on salinity evolution of sea ice during freeze up (ongoing)
- Lab experiments on salinity evolution of sea ice during melting (from January 2011)
- Further development of wire harp for 3-D salinity measurements (ongoing)
- Field experiment on salinity evolution of sea ice during freeze up (Greenland, data processing ongoing)

Modelling the salinity evolution of sea ice

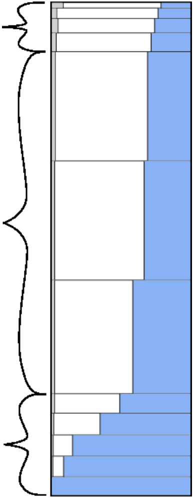
Activities

- Development of enthalpy-based sea-ice model with salinity evolution (ongoing, see next slides)
- Implementation into large-scale climate model (from January 2011)
- Implementation into large-scale climate model with unstructured grid (from May 2011)

Enthalpy based sea-ice model

1D thermodynamic characteristics

- Each layer is defined by enthalpy, absolute salinity, mass and thickness.
- Contains ice, brine and gas
- No explicit water-ice border
- Thin top and bottom layers
- Thickness of middle layers variable



Model desalination

Brine expulsion

- Controls density
- Necesarry for conservation
- Leads to minimal salt and energy flux
- Useful to compare with exact solution

Flushing

- Not implemented (yet)
- Direct application of Darcy's Law
- Remaining meltwater is treated as runoff

Model desalination

Gravity drainage

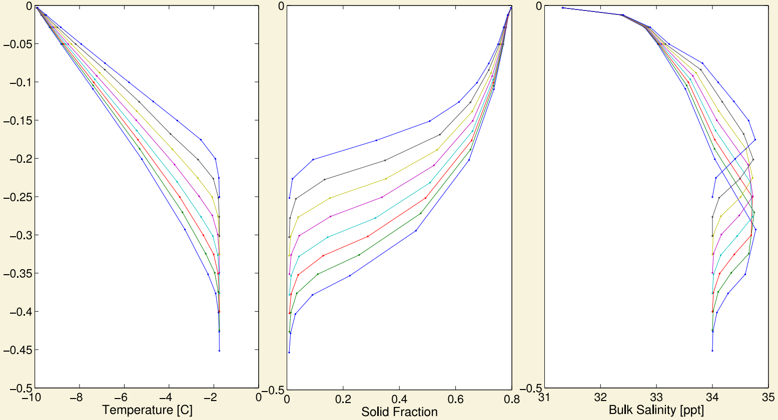
- Requires certain conditions of *Ra*
- We assume *Brine flux* $\sim$ *Ra* which leads to

$$\frac{\partial S}{\partial t} = -const \frac{\partial}{\partial z} \left(Ra \frac{\partial S_{br}}{\partial z} \right)$$

- Brine flux is determined by ϕ_z and $S_{br\,z}$
- Entails small energy flux
- Issues: Parametrization of permeability and Rayleigh-number dependence, no consideration of frazil ice formation (yet)

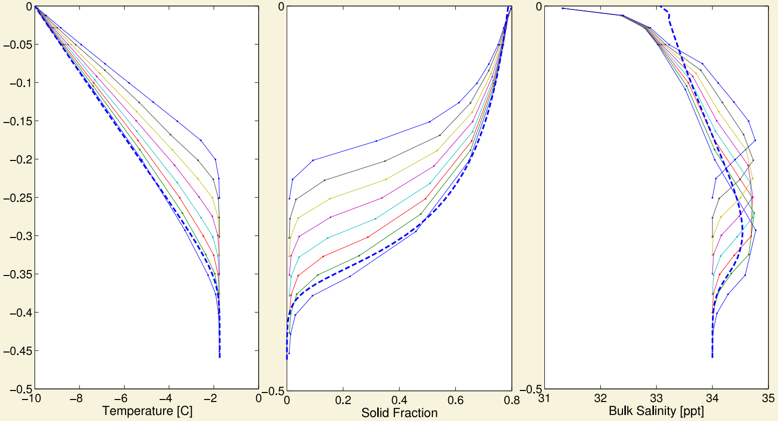
Expulsion test

Temperature, solid fraction and bulk salinity evolution over 10 d



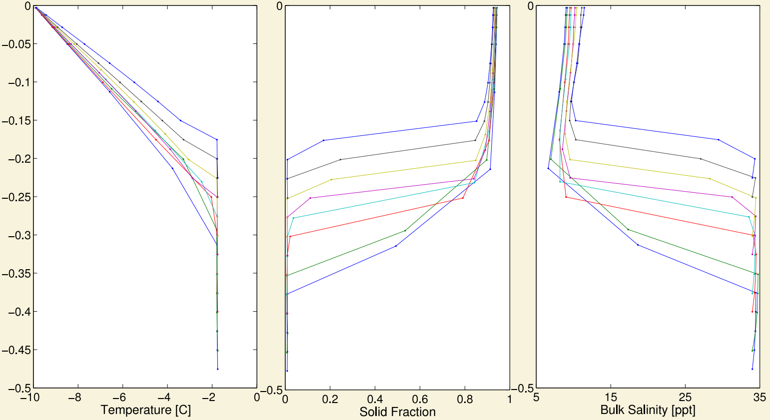
Expulsion test

Temperature, solid fraction and bulk salinity evolution over 10 d



Gravity drainage test

Temperature, solid fraction and bulk salinity evolution over 10 d



Outlook

1D dynamics

- Finalize gravity drainige and flushing
- Implementation of gas
- Determine optimal vertical grid

GCM

- Static unstructured grid
- Subscale distribution ?
- Advection ?

Summary

Only two processes matter...

These processes can be neglected when modelling salinity evolution in a large-scale coupled model:

- Initial salt rejection
- Brine expulsion
- Salt diffusion

Hence, only two processes are important that need to be understood:

- Gravity drainage
- Flushing